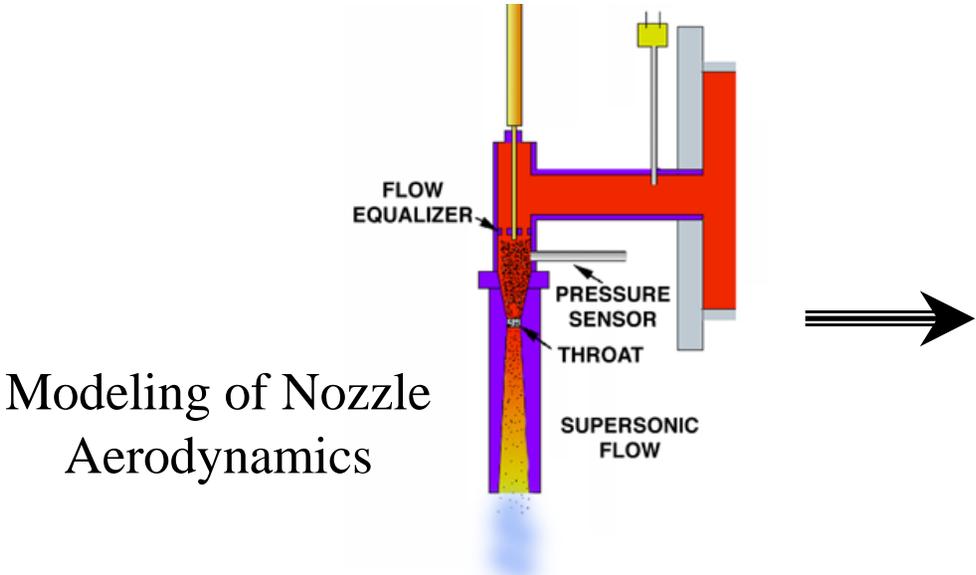




Sandia's Approach to Cold Spray Research

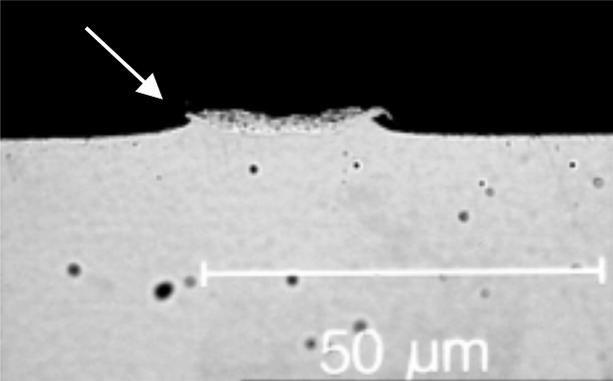
Combine experiments with modeling & diagnostics to optimize performance



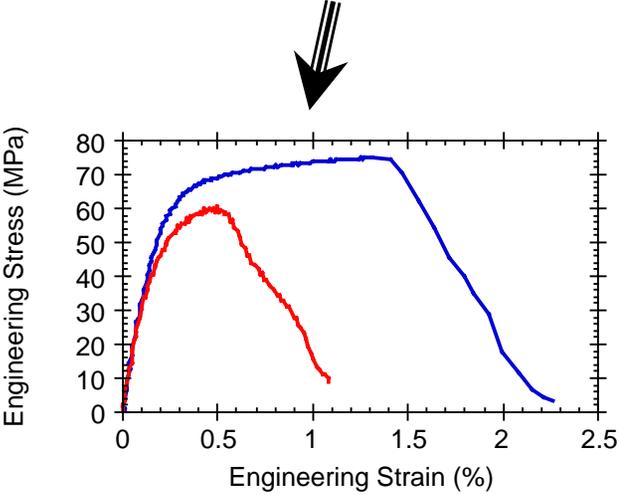
Modeling of Nozzle
Aerodynamics

In-flight Particle
Diagnostics

Particle-substrate interactions



Deposit properties

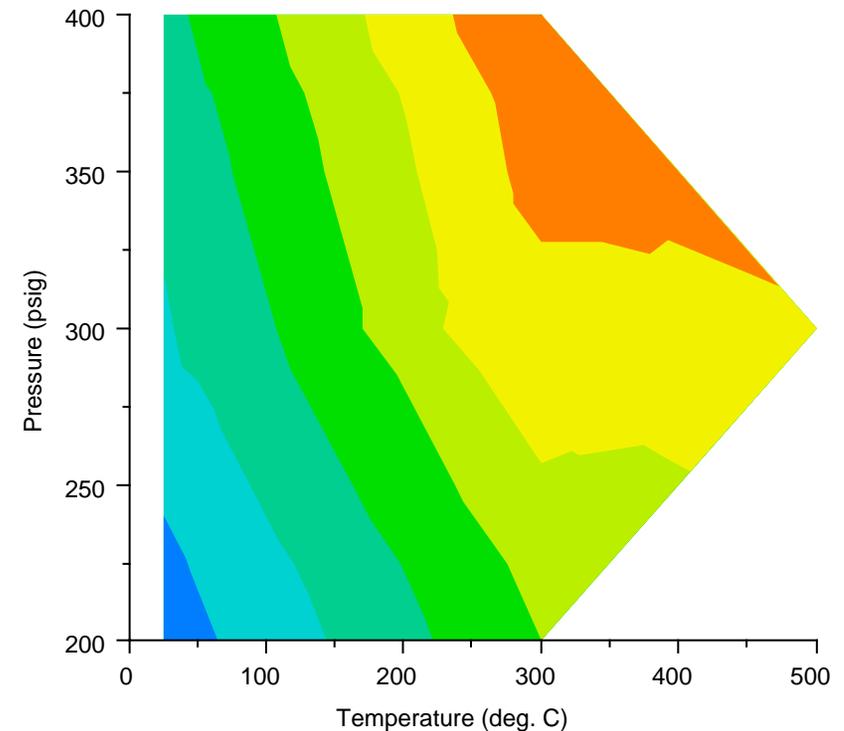


In-flight Particle Diagnostics & Parameter Sensitivity



**Thermal
Spray
Research
Laboratory**

- Particle velocities are affected by:
 - Particle size
 - Particle density
 - Gas velocity
 - Gas density
 - Nozzle length
- Gas velocity & density are affected by:
 - Supply pressure
 - Pre-heat temperature
 - Gas type
 - Nozzle design
- Particle velocity distribution is relatively constant within the plume

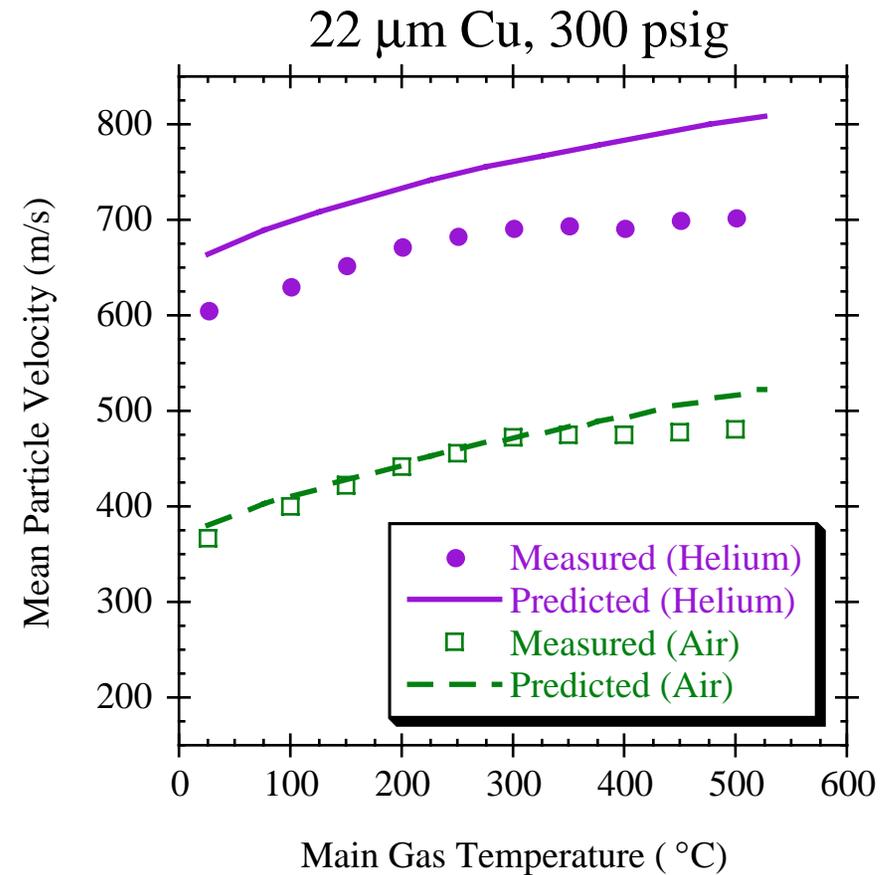
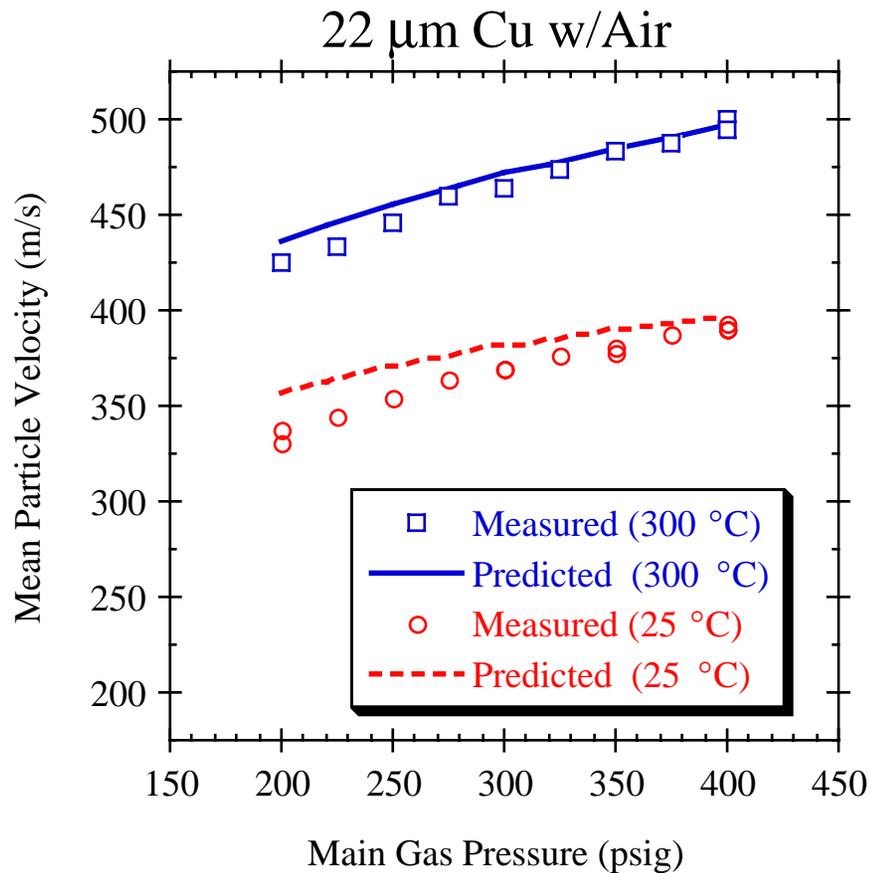


Velocity (m/s)	Color	Velocity (m/s)	Color
<= 350.0	Blue	<= 425.0	Green
<= 375.0	Cyan	<= 475.0	Yellow
<= 400.0	Light Green	<= 500.0	Orange
<= 450.0	Yellow-Green	> 500.0	Red

In-flight Particle Diagnostics & Parameter Sensitivity



- Particle velocity variations with gas pressure, temperature, type

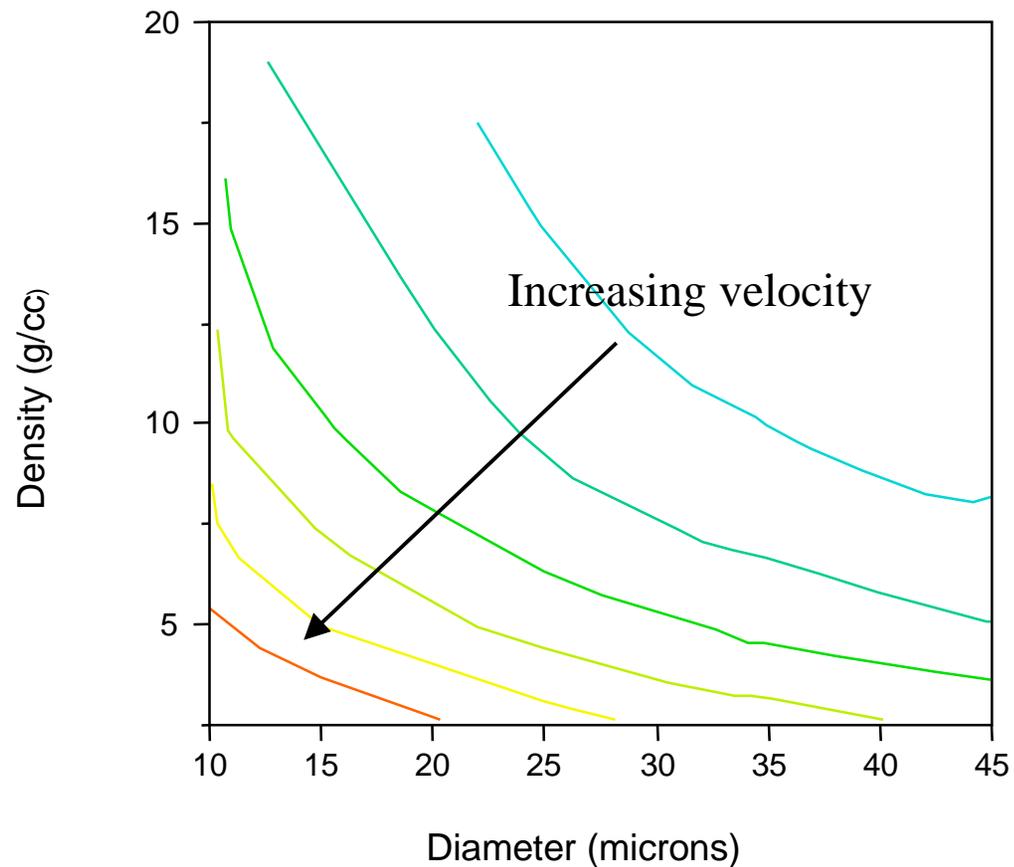


In-flight Particle Diagnostics & Parameter Sensitivity



Thermal
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Research
Laboratory

- Particle velocity varies inversely with particle size & density

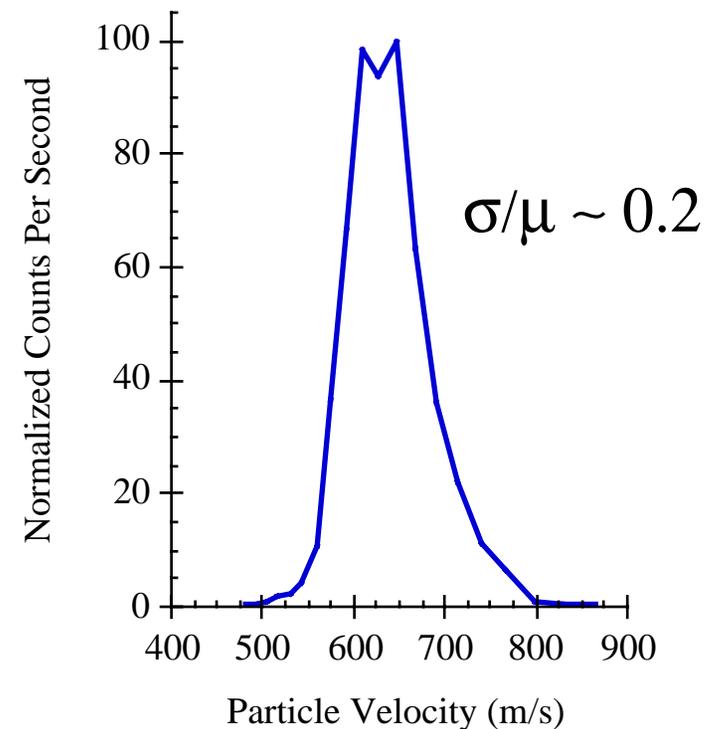
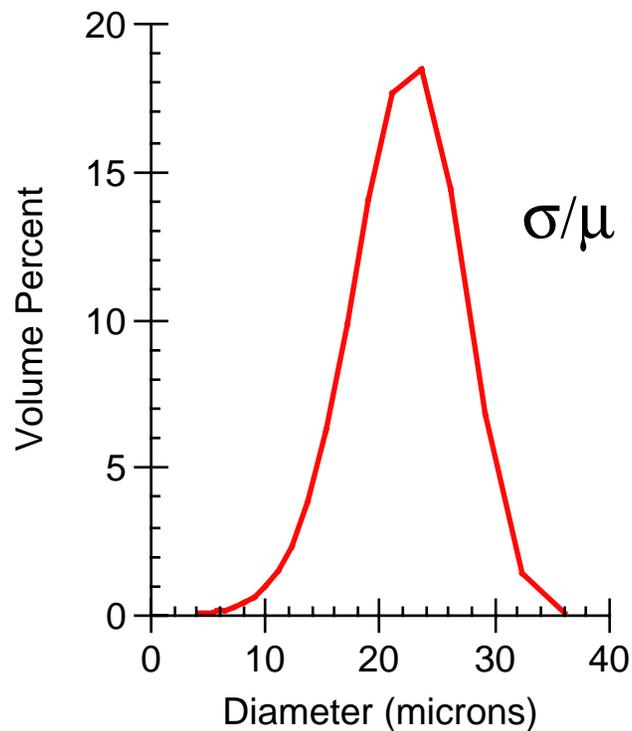


In-flight Particle Diagnostics & Parameter Sensitivity



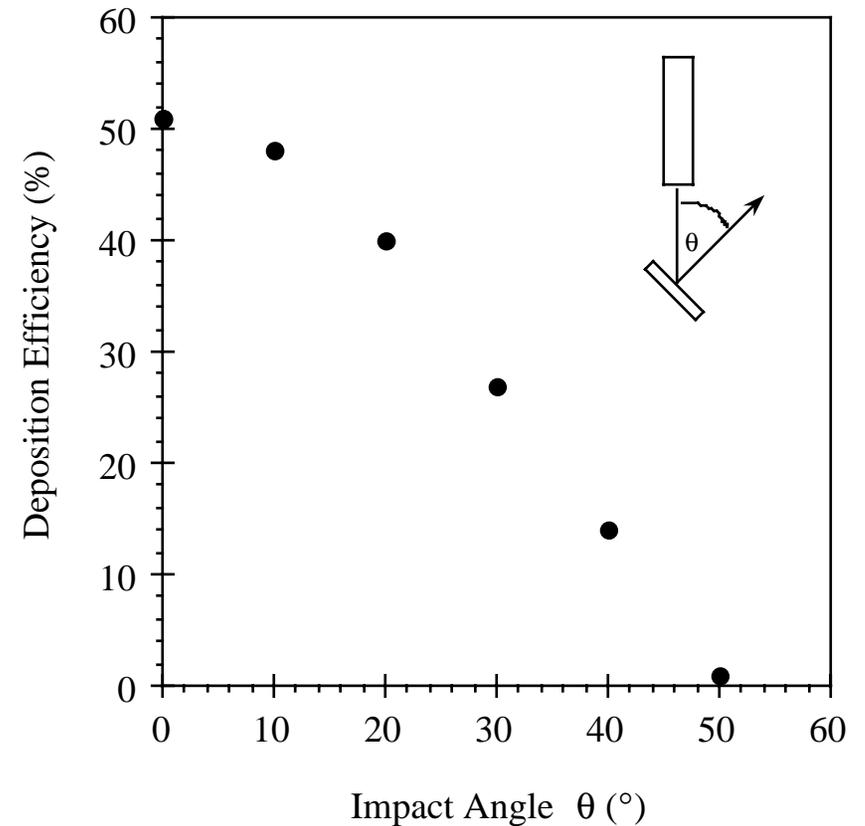
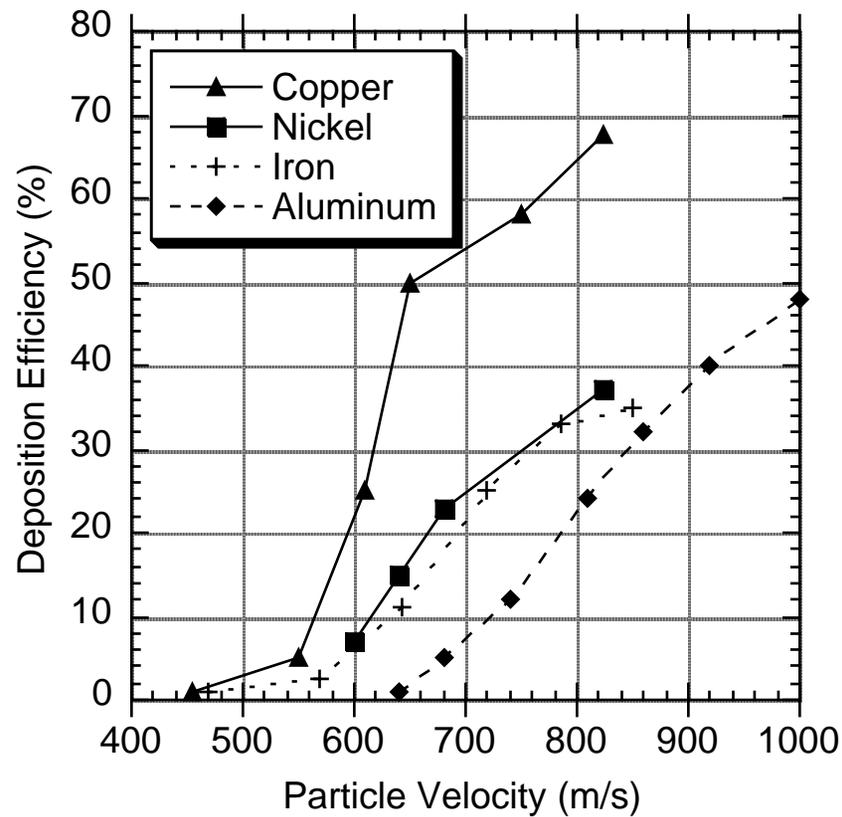
Thermal
Spray
Research
Laboratory

- Particle size distribution causes particle velocities to vary
- Normalized standard deviation of V_p is about half that of d_p , as expected
- Narrow powder size cut is highly desirable



Deposition efficiency

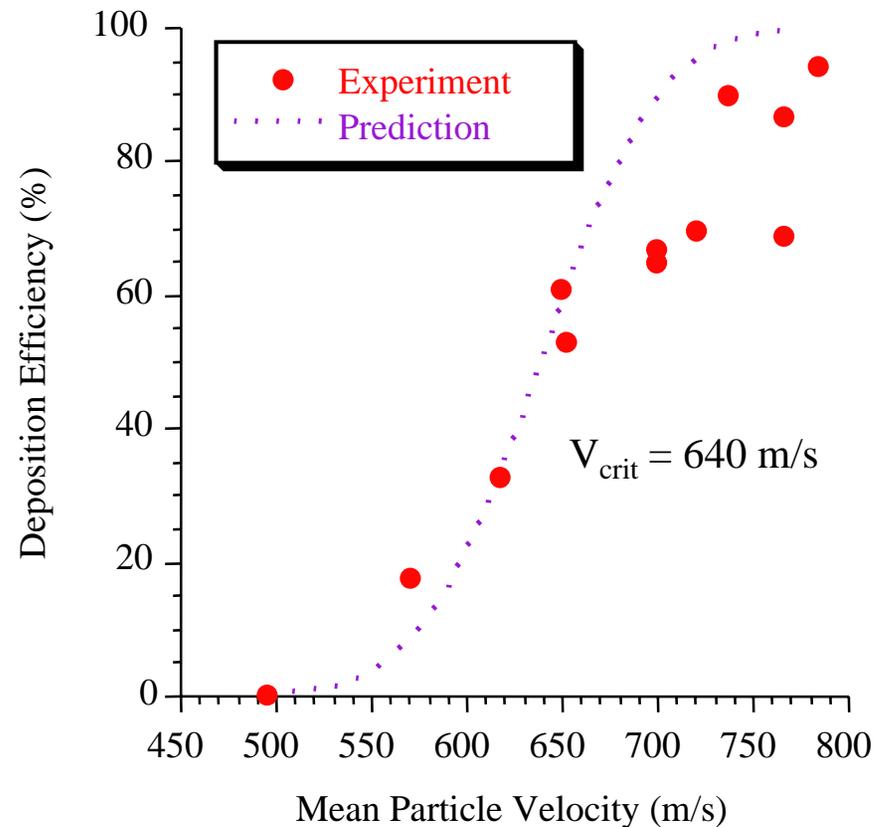
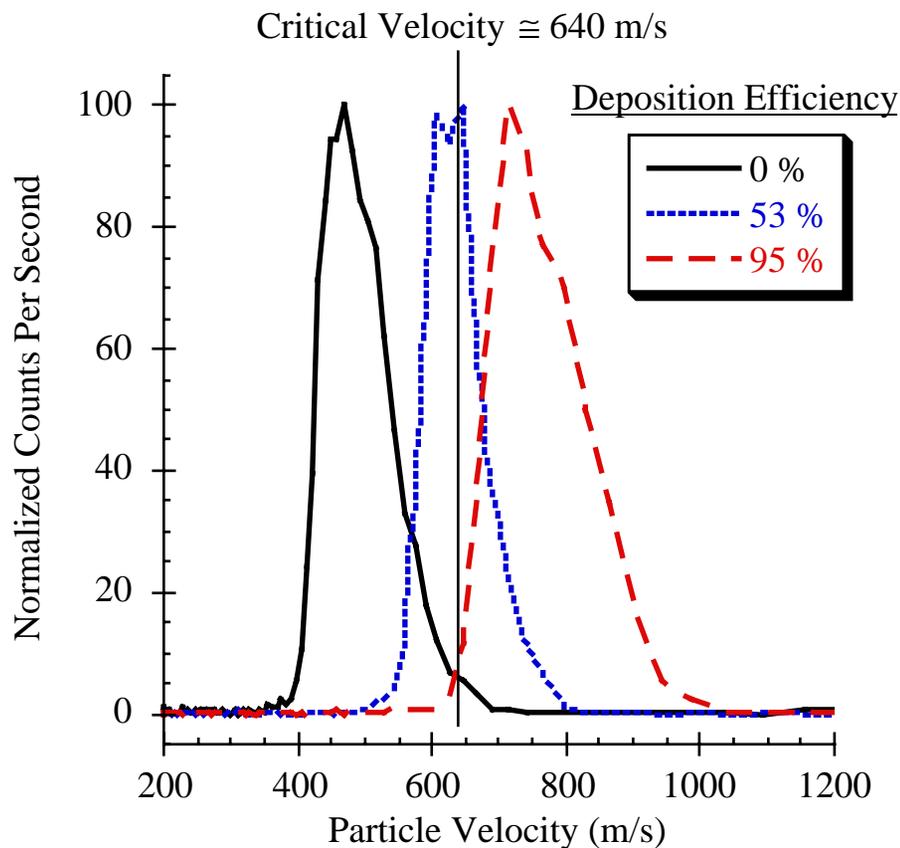
- Varies with particle velocity, impact angle
- Also varies with powder, substrate materials





Deposition efficiency

- There exists a minimum critical velocity for deposition
- Given this V_{crit} and the spread of particle velocities around the mean, the deposition efficiency curve can be calculated



Deposition efficiency

- Modeling critical velocity will allow prediction of deposition behavior for untried material combinations
 - May also give insight into nozzle fouling
- Experiments to model critical velocity
 - Critical velocity should be controlled by physical & mechanical properties
 - Varying alloys, powder heat treatments, substrates
- Poorly understood areas
 - Aluminum vs. copper on alumina & glass
 - Aluminum bronze DE more like aluminum than copper
 - A on B vs. B on A



Materials Sprayed at Sandia

- Copper
- Austenitic, martensitic stainless steels
- Aluminum
- Aluminum bronze
- Nickel alloys
 - Monel
 - NiCr
 - NiCrAlY
- Titanium (w/ & w/o shrouding)
- Tantalum
- Molybdenum
- Cermets
 - WC-Co
 - NiCr-Chrome Carbide

Easy



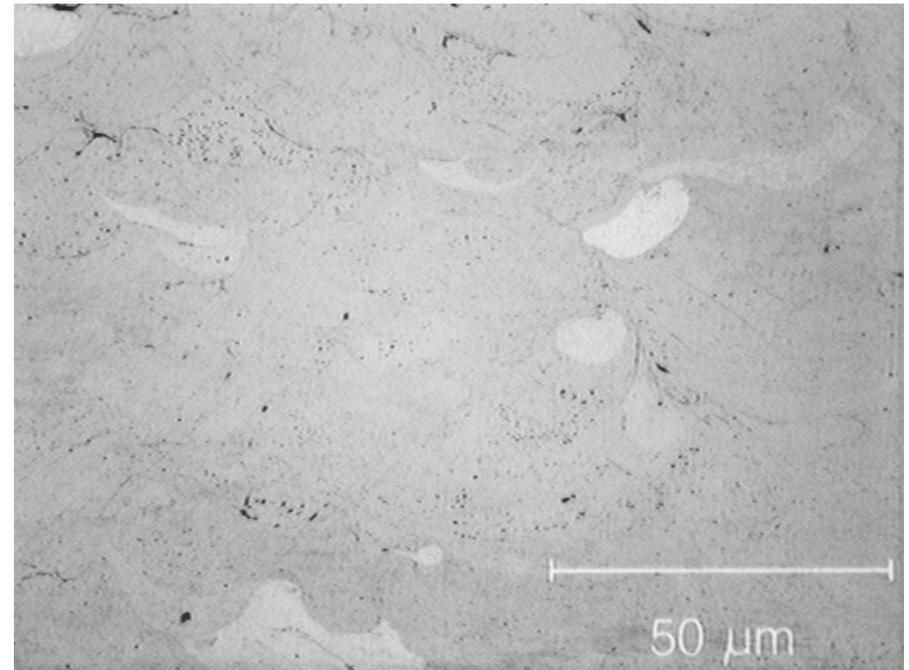
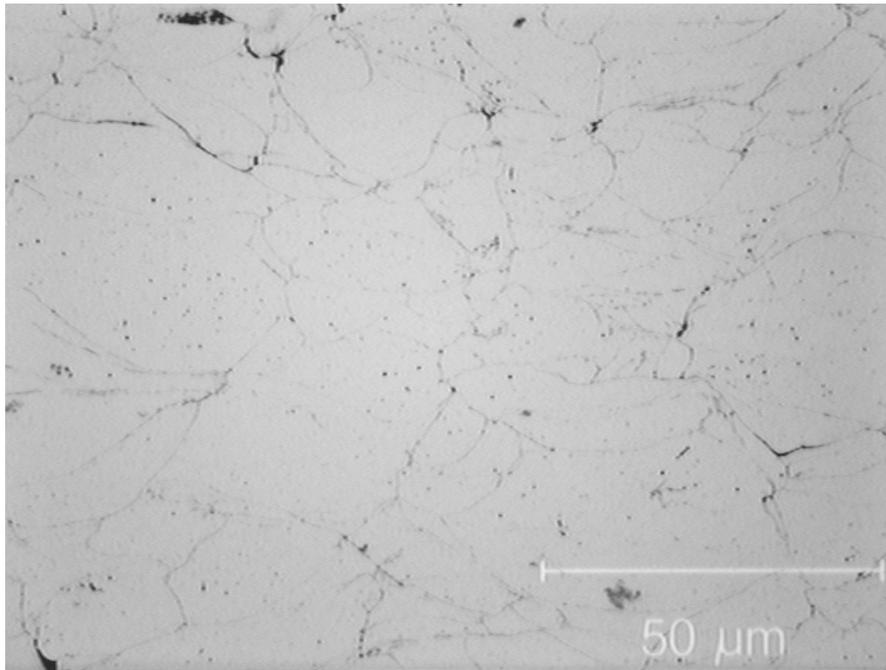
Difficult

Deposit properties - porosity & oxides



Aluminum

Copper



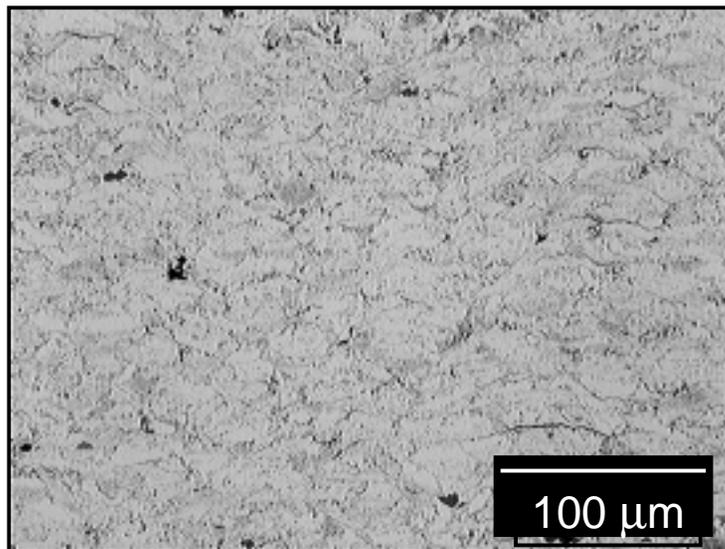
98.5% dense; 0.4 wt% oxygen
(powder oxygen content 0.3 wt%)

99.6% dense; 0.3 wt% oxygen
(powder oxygen content 0.3 wt%)

Deposit properties - Cold Spray vs APS

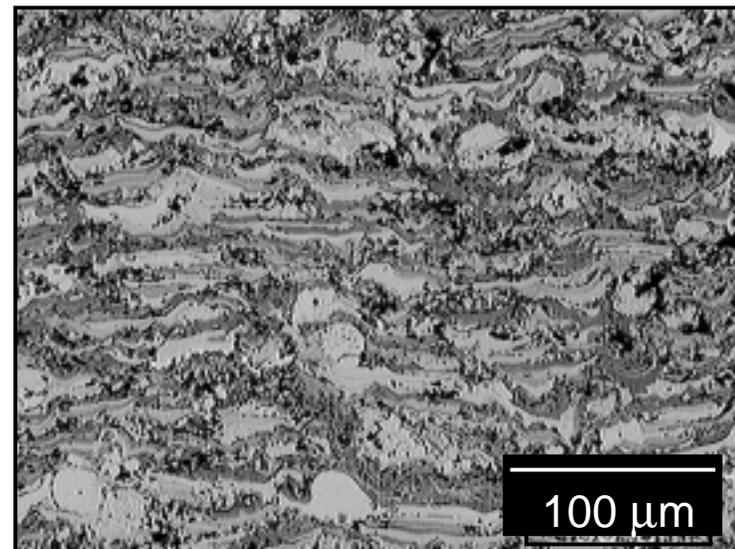


Cold sprayed copper (etched)



Oxide content = 0.3 wt%
Thermal conductivity = 317 W/m-K
(80% OFHC)

APS copper (etched)



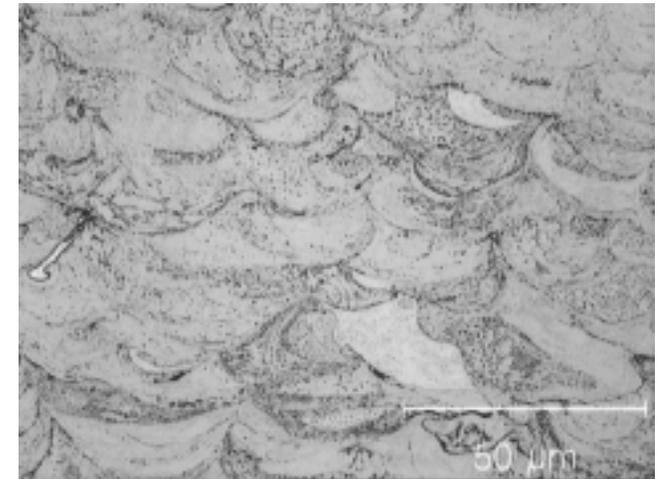
Oxide content = 1.7 wt%
Thermal conductivity = 58 W/m-K
(15% OFHC)

Deposit properties

Mechanical & Microstructural



- Large impact deformation gives CS coatings wrought properties, compressive residual stresses
- As-sprayed grain size for copper ~ 40 nm
- Retain powder phase content (nano WC-Co, Fe₃Pt), or heat treat for novel microstructures



Etched Copper Deposit

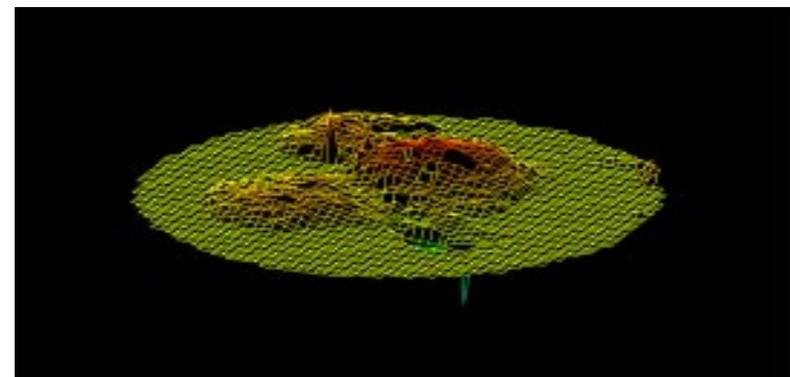
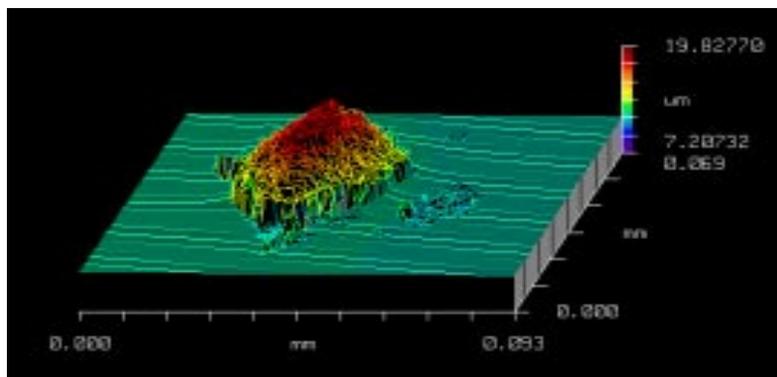
Hardness (Brinell)

	<u>Cold Spray</u>	<u>Bulk (Annealed/Full Hard)</u>
1060 Al	55	19 / 35
10% Al Bronze	280	140 / 175
420 SS	200	200 / 500
Cu	50 / 150	20 / 110
WC-Co	900-1200 (HV)	



Deposit properties -Residual Stresses

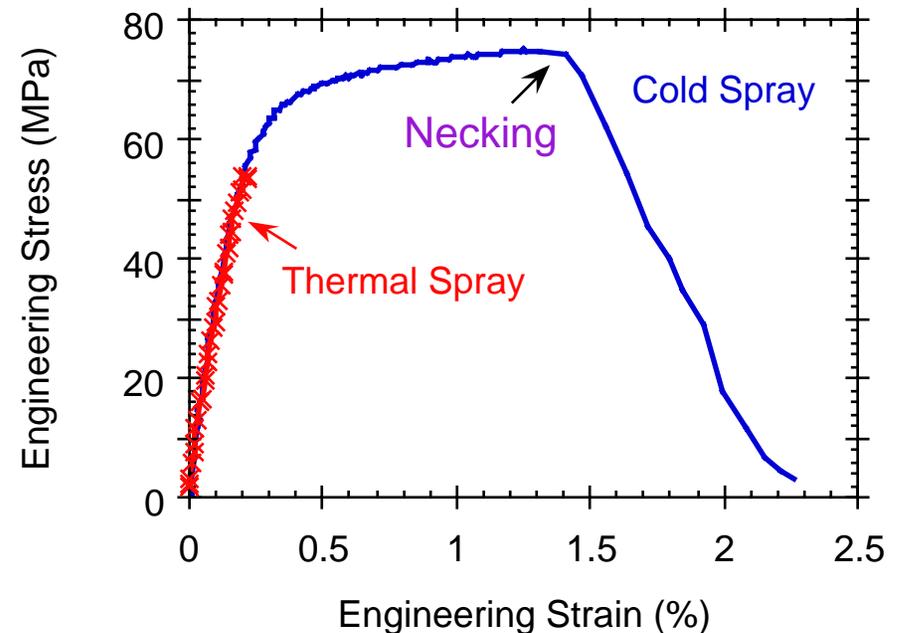
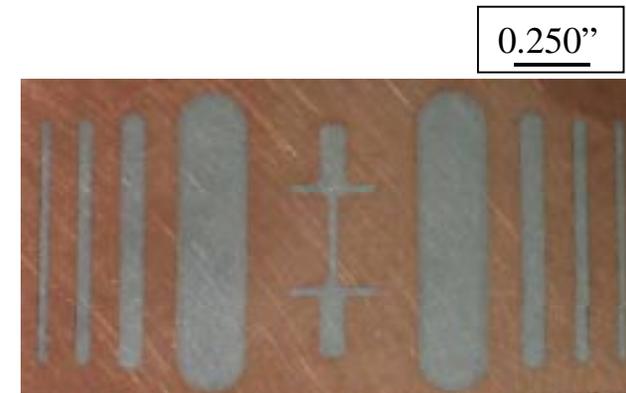
- Residual stress in a 2 mm thick Cu deposit on Al substrate (by neutron diffraction): -84 ± 8 MPa (*compressive*)
- Single splat stresses (by x-ray microdiffraction):
 - -27 ± 17 MPa for Al on glass; -20 ± 18 MPa for Cu on 304 SS
- Results similar to those reported by McCune et al.
- **Compressive stresses should improve bond strength & fatigue performance**





Deposit Properties - Tensile Behavior

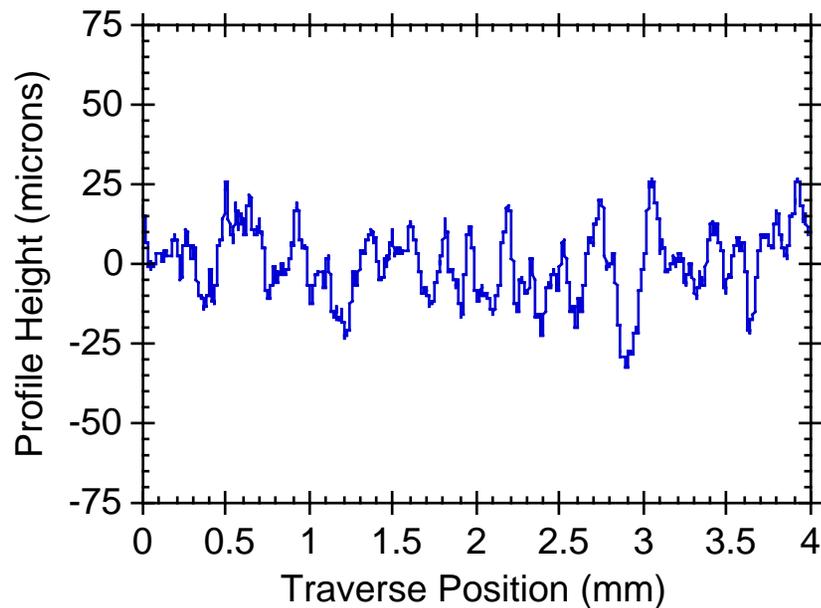
- Aluminum tensile specimens were made for investigation of possible LIGA applications
- Annealed CS samples had a σ_{YS} of 86 ± 11 MPa (~ AA1100 H14 temper)
- Average modulus of CS samples was 34 GPa (50% of bulk, 36% higher than thermal spray)
- Thermal spray specimens broke before yielding occurred; cold spray specimens exhibited ductile failure



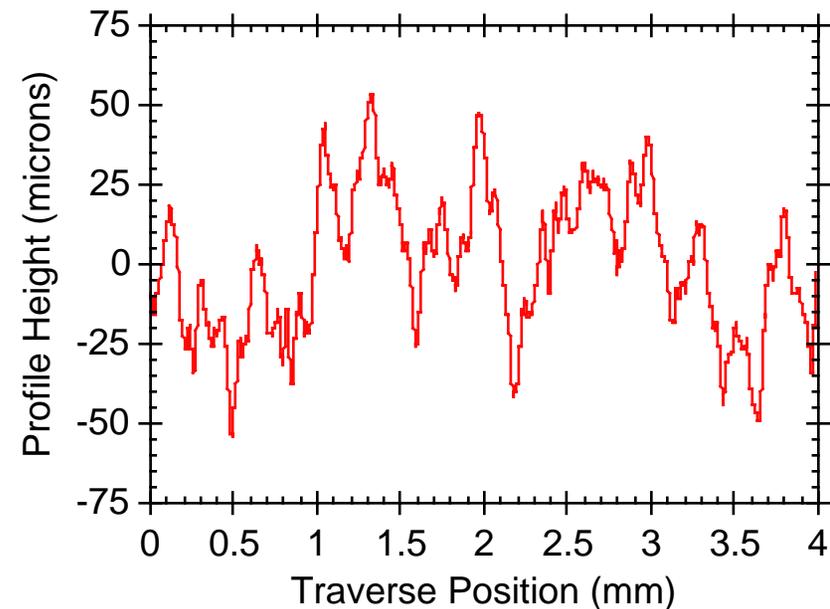
Deposit properties - surface roughness

- Typical $R_A \sim 4 \mu\text{m}$ (160 μin) - about half that of a flame sprayed coating
 - Likely due to fine powder size cut

Cold Sprayed Copper
(vertical exaggeration 20x)



Flame Sprayed Copper
(vertical exaggeration 20x)





Thermal
Spray
Research
Laboratory

Conclusions

- Particle velocity controls deposition efficiency and coating quality
- Further work remains to understand the material parameters which govern the critical velocity for deposition
- The properties of cold spray coatings are superior to those of thermal spray coatings for many materials & applications
 - Low oxide content & low porosity \Rightarrow high conductivity
 - Compressive residual stresses
 - Significant tensile ductility; wrought properties
 - Low surface roughness
 - Fine grain structure & retained powder chemistry